PROCEEDINGS OF THE FIRST SYMPOSIUM ON HIGH ENERGY PHYSICS

INDIAN INSTITUTE OF TECHNOLOGY, BOMBAY
DECEMBER 12-16, 1972

Editors

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PREFACE

The First Symposium on High Energy Physics was held during December 12-16, 1972 at the lovely locale of the Indian Institute of Technology, Powai, Bombay. It was organised by the Tata Institute of Fundamental Research, Bombay, under the auspices of the Department of Atomic Energy, Government of India. The Symposium was inaugurated by Dr. P.K. Kelkar, Director, I.I.T. Powai and Prof. R.R. Daniel, Dean, T.I.F.R., made the opening remarks.

This Symposium was originally scheduled to be held at the T.I.F.R. itself but unfortunately the venue had to be shifted as the accommodation which was arranged for the delegates had to be provided to the emigrants returning from Uganda. Fortunately, Dr. Kelkar, Director, I.I.T., Powai, was kind enough to offer not only the required accommodation but also all the facilities necessary for holding the Symposium. We are indeed grateful to Dr. Kelkar and the Physics Department, I.I.T., for coming to the rescue in such a graceful manner.

Although this Symposium has been called the First Symposium in High Energy Physics it could as well have been called the Twelfth Symposium on High Energy Physics since there have been to date eleven other symposia covering the overall areas of Cosmic Rays, Astrophysics and High Energy Physics. A list of these is included at the end. However as this is the first symposium since a decision regarding the 'split' was taken, it is appropriate to recount here a brief history of the symposium and the considerations which led to such a decision.

The history of the 'symposium' is intimately related to the development of cosmic-ray research in India, which was initiated in the country during the late 40's. The glamour of cosmic-ray research was due to the importance of understanding the origin and the acceleration mechanism of the cosmic radiation and also because it provided the only means of carrying out studies in the field of elementary particles and high energy nuclear interactions. Because of these reasons cosmic-ray research in India grew at a considerable pace and it was soon realised it would be desirable to hold an annual symposium which would provide a forum for the Indian scientists to exchange ideas.

Around mid 50's, it was realised that cosmic-ray research on the radioisotopes produced in the atmosphere could make important contributions to certain areas of Geophysics. As a result 'Geophysics' was also included within the scope of the subsequent symposia. Although the

potential possibilities of Cosmic ray research to the field of astrophysics were realised quite early, its real impact began to be felt since mid 60's only. It was therefore [illegible] decided to include Astrophysics also among the areas covered by the symposium.

Because of this increased scope of the symposium and considerable growth of research activities in all these areas, the symposium attendance also increased considerably, resulting in acute organisational problems. In the past, attempts were made to hold the symposium at as many different centres of research in the country as possible with the hope that it would give impetus to the research activities of the local institutions. However, the increasing number of scientists desiring to attend the symposium made it difficult to meet this objective because of the organisation problems, e.g. accommodation arrangements put a severe limitation to the number of places where such a large conference could be managed properly.

Moreover, in recent years, research on cosmic rays and particle physics has been diverging from each other. While cosmic-ray studies are now related more to astrophysics than to particle physics, during the last decade and a half particle physics has grown immensely and has become a distinct field in its own right.

In view of the above reasons, the Cosmic Ray, Geophysics, Astrophysics and Particle Physics Committee of the Department of Atomic Energy, in a meeting held on February 28, 1972 decided to split the symposium into two biennial symposia, one on Cosmic Rays and Astrophysics (including aspects of Geophysics related to Cosmic Rays) and the other on High Energy Physics (including aspects of Cosmic Rays related to High Energy Physics, such as studies involving Extensive Air Showers, muons and neutrinos). These two symposia are intended to be held on alternate years.

It was this background which led to the start of an exclusive series of biennial symposia on High Energy Physics, of which the present one is the first.

A special feature of this symposium was the introduction of panel discussions on topics of considerable current interest. There were two panel discussions, one on "Strong Interaction Dynamics and Phenomenology" and the other on "Hadron Symmetries, Their Breaking and Related Topics". Both of these turned out to be very lively indeed. Their success was largely due to the fact that the panel members had done their 'home work' well and there was considerable participation from the floor. It is hoped that panel discussions would become a recurring feature of the future symposia in this series.

Other special features of the symposium were, (i) an evening talk on "Shadow and Substance" by E. C. G. Sudarshan and (ii) three reports o the 16th International Conference on High Energy Physics held at Chicago Batavia during September 6-13, 1972, which essentially brought the excitement of this Conference to the doorsteps of the delegates.

The proceedings contain the invited talks and summaries of panel discussions. In accordance with a prior decision, contributed papers ha not been reproduced: however, a list of all the contributed papers submit to the symposium is included.

In order to minimise delay photo-offset process has been used fo publication with a minimum of editing. Nevertheless, there has been considerable delay in bringing out the proceedings. This is mainly due t the fact that a number of manuscripts were received well beyond the nominated deadline.

We would like to thank our colleagues on the Organising Committ and the Local Organising Committee for their contribution towards succe of the Symposium. We are grateful to the staff and the students of the Physics Department, I. I. T., in particular Professor B. N. Bhattacharya for their great help and co-operation. We are thankful to B. Radhakrish A. K. Raina and G. Bhattacharya for their help.

We would like to thank Dr. V. A. Kamath for his unstinted help an co-operation in bringing out the proceedings.

Finally, on behalf of the Organising Committee, we would like to take this opportunity to express our gratitude to the Department of Atomi Energy for providing the necessary funds for the symposium.

P. K. MALHOTRA
V. GUPTA
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CONTENTS

HIGH ENERGY INTERACTION CHARACTERISTICS FROM EAS STUDIES

B.V. Sreekantan
Tata Institute of Fundamental Research, Bombay 5.

I would like to begin my talk by narrating an episode that took place about 24 years ago which may have some relevance to the thinking that goes into the planning of the future of high energy physics, a topic reference to which was made this morning. The incident took place in 1949 when TIFR had just moved from Kenilworth in Pedder Road to the Yacht Club building at the Gate Way. Some of us were in the process of setting up a 12" diameter cloud chamber for cosmic ray investigations and had negotiated with a British firm for the purchase of a suitable magnet to go with it. Just at this time an eminent physicist who had himself spent several decades in cosmic ray research, visited us and when he was told about the proposal for the purchase of a magnet for the cloud chamber, said that we were too late and that practically all investigations in cosmic rays using cloud chambers, particularly magnet cloud chambers, had been exhausted by groups abroad and strongly advised us against spending on a magnet costing about a lakh of rupees. Naturally we had to abandon the idea of a magnet for the chamber. Ironically, a few months later the same scientist visited us again and talked to us at the Yacht Club lecture theatre about the discovery of V-particles, a discovery which had been made using a magnet cloud chamber of roughly the same dimensions as the one that we had. As perhaps some of you here know, the next 5-6 years, between 1949 and 1955, were the hey-days for cloud chamber investigations. Very sophisticated set ups came up in Jung Frau Jock and Pic Du Midi

and heavy nuclei has been used for this purpose for over two decades at balloon altitudes and more recently at satellite altitudes. The secondary cosmic ray beam consisting of pions, kaons and nucleon-antinucleons has been used at mountain altitudes. Nuclear emulsion stacks, magnetic and multiplate cloud chambers, ionisation calorimeters, total absorption spectrometers, multi gap and wide gap spark chambers have been used for these investigations either singly or in combination. Some important conclusions regarding the characteristics of high energy collisions at energies below 10^{15} eV have been derived from the study of unassociated hadrons and gamma rays at various depths in the atmosphere and from the study of the high energy muon component at sea level and underground. Without going into the experimental details and the analysis procedures, I will summarise the main results from these experiments for energies less than 10^{15} eV.

(i) Inelastic cross section

Some experiments have shown that the inelastic cross section increases with energy. With the ionisation calorimeter set ups on the Proton Satellites, Akimov et al.[2] have measured the transmission of primary protons through Carbon and Polythene targets and have come to the conclusion that σ_{inel} (C) increases by about 20% from 20 to 200 GeV and σ_{inel} (H) also increases but at a much slower rate (Fig. 1). The measured rate of rise can be expressed by

$$\sigma = \sigma_o \left(1 + a \ln \left({}^{E}/_{E_o}\right)\right)$$

where E is in GeV, a ~ 0.1, E = 50 and σ_0 = 210 mb.

Using the results on the energy spectrum of hadrons in the atmosphere at various altitudes, Yodh et al.[1] have shown that σ_{inel} (air) would increase with energy from 235 mb at > 50 GeV to ~ 350 mb and then saturate between 3×10^{12} and 10^{15} eV, if the primary spectrum is given by A $E^{-1.67}$. If, on the other hand, the steepening of the primary proton spectrum as reported by Akimov et al. is taken into account, then the same results on the hadron spectra would mean, according to Yodh et al. that σ_{inel}(air) would rise to a broad maximum around 2×10^{12} eV and then decrease to a plateau value of 280 mb at 3.10^{13} eV.

However, the rise in cross section is not supported by the experiments of Bussian et al.[3] carried out at Echo Lake using liquid hydrogen target for the study of interactions of cosmic ray hadrons. They find that the inelastic p-p cross section remains constant in the energy range 10^{11} - 8×10^{11} eV and has the same value as at low energies. Similar is the conclusion of Dashindjhagr et al.[4] for proton-carbon, proton-iron and proton-lead interactions. As we shall see, at air shower energies there is again some evidence for an increase in the cross section. At the moment therefore there is a controversy regarding the increase of inelastic cross section with energy.

(ii) Inelasticity

It is through cosmic ray investigations in the early 50's that it became evident that nucleon-nucleon collisions are not

Features of high energy interactions extracted from air shower studies

The flux of primary cosmic rays of energy $> 10^{16}$ eV is about 1 particle/m^2/year. It is evident therefore that flux considerations make it impossible to study individual interactions using the cosmic ray beam at these super high energies even with the next generation of satellites and space platforms. The only method available is the method of extensive air showers. In this method the characteristics of collisions have to be deduced from observations on the end-products of many generations of strong, weak and electromagnetic interactions that proceed in the atmosphere following the arrival of a primary particle at the top of the atmosphere. In spite of the method being an indirect one, in recent years it has been possible to elicit certain features of ultra high energy interactions rather unambiguously because of two developments. With the sophisticated air shower arrays it has become possible to obtain detailed information on various aspects of air showers - electron, muon, hadron components, Cerenkov radiation, radio emission etc. and also to classify the data according to shower size, stage of development of the shower, correlation between the different components etc.; with the advent of fast computers it has now become possible to carry out four-dimensional cascade calculations from which both the longitudinal and lateral structures, as well as the time structure of the

different components can be rigorously evaluated incorporating into the calculations variations in the values of the different parameters of high energy collisions and take cognisance of different collision models. I would like to illustrate the power of the EAS method by a few specific examples. I shall deliberately confine myself only to our own efforts in this field over the past few years. In our Ooty air shower array we measured the time structure of hadrons of different energy in the size range $10^5 - 10^7$ particles. Fig. 2 shows a typical time distribution for the hadrons of energy 10-20 GeV. On the basis of different models of interactions, we calculated the expected time distributions. It was evident from the comparison that unless we incorporated a considerable increase in the production of $N\bar{N}$'s the observed time structure could not be reproduced. $N\bar{N}$ production to the extent of about 15% in collisions of energy $\gtrsim 10^{12}$ eV was found to be necessary.

A second parameter which has been measured at Ooty and which shows up the necessity for a further rise in the cross section for the production of $N\bar{N}$'s at energies $\gtrsim 10^{14}$ eV, is the charged to neutral ratio of hadrons in air showers, which has been determined by operating a large multiplate cloud chamber at the centre of the EAS array. The experimental results show (see Table 1) that the ratio for hadrons of energy $\gtrsim 25$ GeV is rather low - of the order of about 6 or so, for showers of size $\lesssim 3.10^5$ and decreases further to a value of about 3 for larger size. If $N\bar{N}$ production is not taken into account, then most of the hadrons will be pions and the

charged to neutral ratio will be very high - of the order of 30 or more. The decrease in the C/N ratio from a value of 6 to 3 suggests the necessity for a further increase in the $N\bar{N}$ production.

Let us consider a feature of air showers which is sensitive to the interaction mean free path and inelasticity of the primary particles. In the figure 3 we have given the experimentally determined fractional hadron energy spectra for two different size groups. The energy of the hadrons is expressed as a fraction of the primary energy of the particle initiating the shower. Only hadrons of energy $>$ 200 GeV have been considered for this plot. The curves that have been drawn in the figures correspond to the calculated fractional hadron spectra of the primary surviving particles at the observational level. The different curves are for primaries of different atomic number. The calculated spectrum is dependent entirely on two parameters λ, the interaction mean free path and ε, the inelasticity in the collisions of the primary particle with air nuclei. It is seen that the experimentally observed spectra fall much below the primary survival spectra calculated for the pairs of values λ = 80 gms/cm^2 and ε = 0.5, and λ = 80 gms/cm^2 and ε = 0.6. Further it is noticed that the experimental spectra are different for the two size groups. The survival spectra may be brought into agreement with the experimentally observed ones for showers of size less than 3 x 10^5 if we use for λ a value of 67 gms/cm^2 and for ε a value of 0.5 or retain λ at 80 gms/cm^2 and change ε to 0.4. But the same set of values do not

fit the data for showers of size $> 3.10^5$. If we want to attribute the experimentally observed spectra to secondaries produced in the collision rather than the survivors, it is clear that the values of λ and/or ε will have to be still more radically different so that the survival spectra fall very much below the observed ones.

A parameter which is sensitive to the probability of formation of isobars in high energy collisions is the high energy muon component, since this arises essentially from the decay of the isobars. In figure 4 we have shown the variation of the total number of muons of energy $\geqslant 220$ GeV and $\geqslant 640$ GeV as a function of shower size obtained with the KGF air shower array. An interesting feature to be noticed is the rather slow increase in the number of high energy muons with size. Calculations based on conventional models give a much faster rise, the slope of the $N_\mu - N_e$ curve being almost 1. The experimentally determined slope has a value of ~ 0.4. It has been shown by Sivaprasad(13) that the observed slow rate of increase could be explained by the hypothesis of a changing primary composition in the energy range $10^{14} - 10^{16}$ eV provided an increase in $N\bar{N}$ *production is taken into account in collisions of energy* $\geqslant 10^{12}$ eV. However, as discussed in our paper(14) the hypothesis of a changing primary composition leads to certain contradictions regarding the properties of air showers. The slow increase of the high energy muon content can be accounted for by decreasing probability of isobar formation at very high energies.

A parameter that is sensitive to the transverse momentum distribution in high energy collision is the lateral distribution of high energy hadrons with respect to the axis of the accompanying shower. The distribution obtained by us for hadrons of energy $\geqslant$ 1 TeV is given in the table 2. It is seen that in showers of size $\geqslant 3 \times 10^5$, hadrons of energy of a few TeV have been recorded upto distances of $\sim$ 5.6 m from the core. The observed distribution is too flat to be explained in terms of core location errors. If these hadrons have arisen or have suffered collision in the previous interaction mean free path, then the observed distribution suggests a rather high p_t - of the order of several GeV. The other possibility is that these hadrons are secondaries produced high up in the atmosphere and leak through the intervening atmosphere. This would require a considerable enhancement in the production of $N\bar{N}$'s at very high energies as discussed by Vatcha and Sreekantan[14].

There are several other features of hadrons and muons in air showers like the absolute number, energy spectra, lateral distribution etc. on which experimental observations are available. The parameters of high energy collisions are required to be adjusted such that the cascade results agree with the experimental results on all these aspects. Additional constraints on the collision parameters come from the need to satisfy the relation between the primary energy and the shower size at the observational level. This particular constraint, in addition to all other constraints as discussed in our papers[14] points to the need for the introduction of a process similar to the gammaisation process proposed

by Nikolsky according to which a considerable fraction of energy is transferred to the soft component by-passing pionisation.

Since there is no time to go into the details, I will just indicate the general trend on the energy dependence of strong interaction characteristics that result from an attempt to bring about a close agreement between experimental results on high energy hadrons and muons and the simulated air shower parameters. The details are available in the three papers which are under publication[14].

At energies less than 10^{11} eV, hadron interactions are only partially inelastic. A large fraction of energy (~ 0.5) is retained by the colliding high energy nucleon which often emerges in an excited isobaric state. As the energy approaches the TeV region the inelasticity increases as also the cross section for interaction. The production of nucleon-antinucleon pairs starts becoming important and at the same time a considerable fraction of energy is occasionally given to the soft component by-passing pionisation. The probability of this 'gammaination' increases with energy. Also as the energy increases the probability of isobar formation decreases, so that a large fraction of the primary energy will not go into a few secondaries. At energies $\geqslant 5.10^{14}$ eV, strong fractionation takes place, isobar formation becomes insignificant, inelasticity increases and the fraction of energy available for 'gammaination' also increases. Also there is a drastic increase in $N\bar{N}$ production and multiplicity has to go as almost $E^{\frac{1}{2}}$.

TABLE I

Charge to Neutral Ratio of Hadrons in EAS

Energy	Size	
	$< 3.2 \times 10^5$	$\geq 3.2 \times 10^5$
25 GeV	6.2 ± 1.3	3.2 ± 0.3

TABLE II

Lateral distribution of TeV cascades

Dist. from core (m) r / Shower size	0 - 1.4	1.4 - 2.0	2.0 - 2.8	2.8 - 4.0	4.0 - 5.6
$\leq 3 \times 10^5$	9/517 1.8 TeV 2.0 TeV 2.2 " 2.5 " 70.0 " 150 " 9.0 " 2.5 " 2.5 "	1/362 1.5 TeV	0/413	0/496	0/493
$> 3 \times 10^5$	11/176 1.0 TeV 2.0 TeV 1.0 " 1.1 " 2.0 " 2.6 " 3.5 " 2.6 " 1.4 " 9.0 " 15.0 " 1.0 "	2/182 4.7 TeV 1.1 "	2/275 1.1 TeV 1.4 "	2/490 9.4 TeV 1.7 "	1/788 2.4 TeV

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<u>ptions for figures</u>

ig. 1 : Variation of the cross-section with energy according to *Grigorov et al.* The lines are empirical fits of the form $\sigma = \sigma_0 \, (1 + a \ln \, E/E_0)$.

ig. 2 : Comparison of the experimental time structure distribution of hadrons of energy 10-20 GeV in air showers of size 10^5, and at distances less than 20 metres from the core, with calculated distributions according to different models of high energy interactions given by Tonwar et al. (1971).

Model A : Primaries are protons; isobar-pionisation with 1% $N\bar{N}$ production at all energies.

Model B : Primaries are all iron nuclei; otherwise same as A.

Model C : Primaries are protons; isobar pionisation with $N\bar{N}$ increasing from 3% at 10^{10} eV to 14% at 10^{13} eV.

Model D : Same as C assuming mixed composition.

Model E : Pure pionisation with enhanced $N\bar{N}$ production as in C.

The best fit with the experimental data is obtained for isobar-pionisation model with increased $N\bar{N}$ production ($\sim 14\%$ at $E \geq 10^{13}$ eV).

ig. 3 : The integral hadron energy spectrum given by Vatcha (1972), in which the energy of the hadron is plotted as a fraction of the primary energy of the associated shower for two size groups $> 3.10^5$ and $\leq 3.10^5$. The curves correspond to the expected integral ene... spectra of the survivors on the basis of dif...

: inelasticity values (ε) and for two values of interaction mean free path $\lambda = 80\ gm/cm^2$ and $68\ gm/cm^2$ and for different primary mass numbers 1, 4, 16 and 64. The dotted line is for a mixed composition. Apart from the fact that the experimental curves are different for the two size groups the significant point to notice is that $\varepsilon = 0.5, 0.6$ and $\lambda = 80\ gm/cm^2$ leads to wide disparity. $\varepsilon = 0.4, 0.5$ and $\lambda = 68\ gm/cm^2$ give better fit.

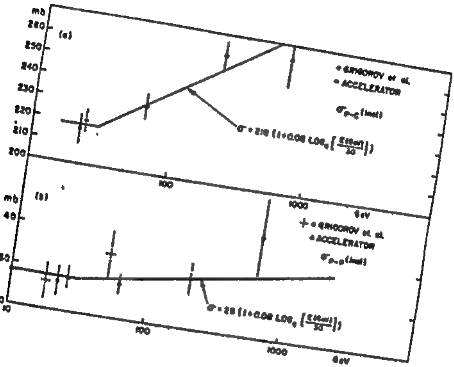
Fig. 4 : Comparison of the calculated and experimentally observed variation of the number of ultra high energy muons ($\geq$ 220 and 640 GeV) as a function of shower size. The calculations are made assuming that the primaries are all protons. In the figure

IB, IBN = Isobar with and without $N\bar{N}$ production

QL, QLN = Quarter Law of multiplicity with and without $N\bar{N}$ production

LL, LLN = Half Law of multiplicity with and without $N\bar{N}$ production

It is seen that the experimentally observed slopes are much flatter than those calculated according to the different models.



mb
260
250
240
230
220
210
200
(a)
• GRIGOROV et al.
• ACCELERATOR
σ_{p-C} (inel)
$\sigma = 210\,(1+0.08\,\log_e\left[\frac{E(GeV)}{30}\right])$
100
1000
GeV
mb
(b)
40
30
20
10
+ • GRIGOROV et al.
• ACCELERATOR
σ_{p-p} (inel)
$\sigma = 28\,(1+0.08\,\log_e\left[\frac{E(GeV)}{30}\right])$
100
1000
GeV

Fig. 1

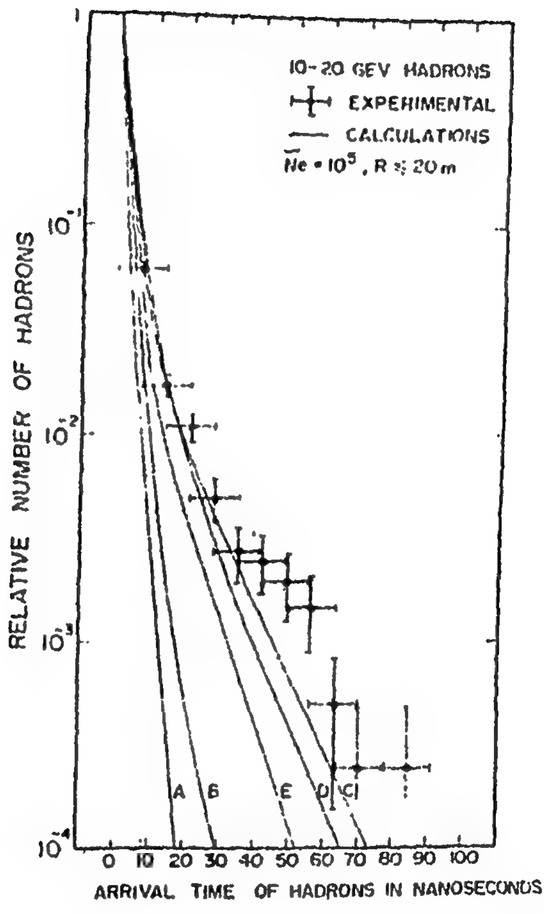

10-20 GEV HADRONS
EXPERIMENTAL
CALCULATIONS
$\overline{Ne} = 10^5$, R ≈ 20 m
RELATIVE NUMBER OF HADRONS
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
A
B
E
D
C
0 10 20 30 40 50 60 70 80 90 100
ARRIVAL TIME OF HADRONS IN NANOSECONDS

Fig. 2

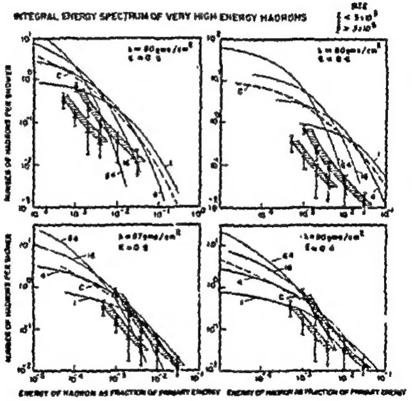

INTEGRAL ENERGY SPECTRUM OF VERY HIGH ENERGY HADRONS
SIZE
NUMBER OF HADRONS PER SHOWER
ENERGY OF HADRON AS FRACTION OF PRIMARY ENERGY

Fig. 5

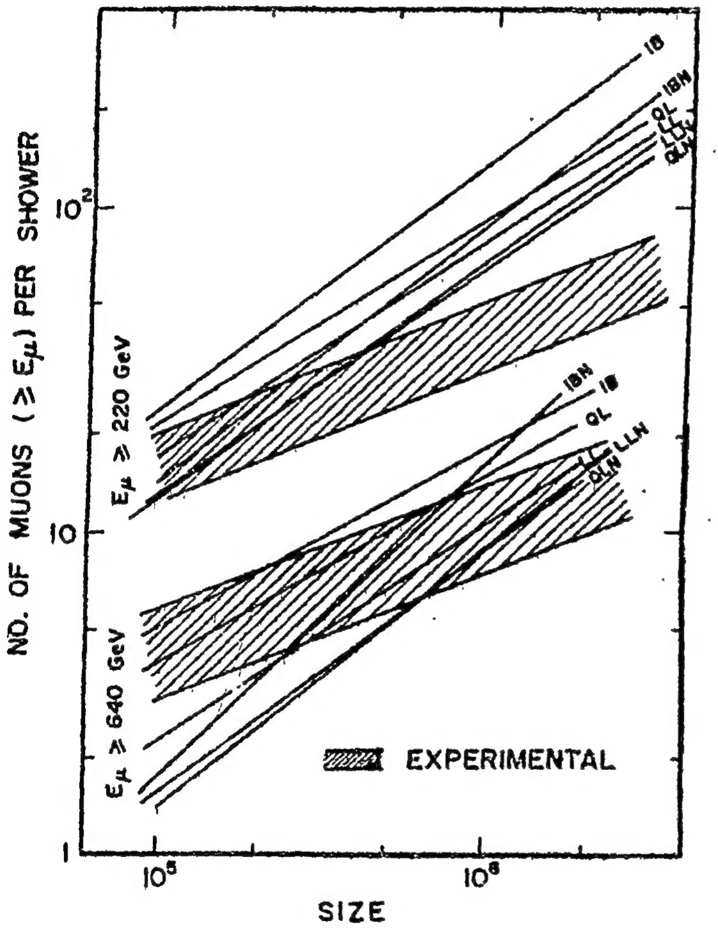

NO. OF MUONS (≥ Eμ) PER SHOWER
SIZE
10²
10
1
10⁵
10⁶
Eμ ≥ 220 GeV
Eμ ≥ 640 GeV
IB
IBN
QL
LL
LLN
QLN
EXPERIMENTAL

Fig. 4

DISCUSSION

Sankaranarayana: All the results that you have summarised regarding evidence from air shower phenomena point in one direction, that collisions are becoming catastrophic at super high energies.

Sreekantan: Yes, that is correct.

Banerjee: With regard to your observation that the mean multiplicity $\langle n \rangle$ increases much more rapidly than lns, I would like to mention the paper of Fishbane, Newmeyer, and Trefil. These authors point out that in most of the earlier determinations of $\langle n \rangle$ for two particle reactions from air shower measurements one did not take into account the effects of multiple scattering of the primary beam inside the target nuclei. It was also shown by these authors that if one did take into account these effects the agreement of the air shower data with the logarithmic growth of $\langle n \rangle$ would be restored.

Sreekantan: In the case of nuclear emulsion studies, it is realised that high values of multiplicity can result due to intra-nuclear cascading. I do not think this is serious in the case of collisions with air nuclei.

Malhotra: I have two comments. (1) I would like to point out that Raghavan and myself had analysed neutral to charge ratio in high energy jets and obtained independent evidence that the production of baryon-antibaryons as well as that of kaons has to be large, 15-20% in the region of 5-10 TeV p

energy (1971 Tasmania Conf. and N.C. 9, 78, 1972).

(2) There seems to be already some evidence that the Satellite results on inelastic cross sections may be unreliable, e.g. at $\sim$ 1000 GeV, the Satellite experiment gives $\sigma_{in} \sim 40$ mb, whereas at the ISR one finds $\sigma_{in} = 32.0 \pm 1.0$ mb.

Prof. Sreekantan has indicated that the EAS data calls for some change in high energy phenomena at EAS energies. The recent ISR experiment by CERN- Columbia-Rockefeller collaboration, reported by Cool at the recent NAL Conference, indicate that whereas for $p_T \lesssim 1$ GeV/c the transverse momentum distribution of π^0 is like $e^{-6 p_T}$, as at lower energies, for $1 \lesssim p_T \lesssim 10$ GeV/c the distribution is much flatter, $\sim e^{-2.5 p_T}$ at $S \sim 2000$ GeV^2. Moreover they find that whereas the first experiment is independent of S, the second seems to decrease with S. These are indeed remarkable results which may indicate new phenomena.

: I would like to remark, regarding high $p_\perp$ events in EAS, that the recent experiment at accelerator energies has found evidence for high $p_\perp$ events, $\langle p_\perp \rangle \gtrsim 0.8$ GeV/c, for reactions proceeding through Baryon exchange mechanism.